



US Army Corps
of Engineers®

Use of Coatings on Hydraulic Steel Structures

Part 1—Overview and Field Survey

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PURPOSE: This technical note is the first in a two-part series that contains information about coatings systems and coating conditions that exist within the U.S. Army Corps of Engineers (USACE or Corps) and the U.S. Bureau of Reclamation (USBR or Reclamation). This work is an effort to capture the state of coating technologies currently used within each organization, as well as to look at past successes and failures. This first volume focuses on the basics of coatings and the results from a field survey.

BACKGROUND AND OVERVIEW: USACE maintains thousands of coated structures throughout its many districts. Many of these structures are subject to harsh environmental conditions that can have adverse effects on the applied coatings. Efforts to provide robust and long-lasting coating systems have yielded a range of successes and failures throughout history. Proper selection, application, regular inspections, and maintenance of these coatings are all crucial for a successful life span.

Many of the Corps' coated structures have been coated far less frequently than what would be considered good practice. This coating infrequency is due to a handful of reasons, which will be explained more fully throughout this document. It is also important to note that coating technology has changed frequently throughout the past century, causing continual changes to standards and guide specifications.

Much of this report contains the knowledge of two coatings experts: one from USACE and one from the USBR. The information was obtained from interviews with personnel from each organization. We thank the experts for their contributions. Their knowledge provided an understanding of the types and uses of coatings systems, as well as common problems and potential improvements.

MOTIVATION FOR COATINGS INSPECTION AND QUALITY CONTROL: There are several motivations for maintaining quality control and inspecting coatings. Longer life, lower costs, and improved performance are key among those motivations. Coatings can be considered a first line of defense for steel structures when trying to minimize or prevent corrosion. For this reason alone, the importance of quality coatings can be understood from a purely economic standpoint. The cost of corrosion to the nation exceeded \$1 trillion annually in 2013 (Jackson 2016). A prior study in 2002 (Koch et al.) reported the cost was \$276 billion. This giant leap in cost over the course of a little more than a decade illustrates a tremendous increase in the cost of corrosion in a relatively short period of time. Money is not the only cost to consider, but the cost in lives also must be considered, as badly corroded structures can fail and cause injury or casualty (such as well-publicized bridge collapses (NACE 2016)). While not always directly attributable to coating

failures, direct and indirect costs of corrosion have reached all-time highs and are expected to climb even higher, up to 1.1 trillion in 2016 (Jackson 2016).

Quality coatings on steel structures that are used for the Corps' navigation and flood-control structures are essential to the nation's waterways. Negative impacts on the operation or control of these structures have far-reaching consequences. Ensuring that coatings are doing their job starts with quality control at the time of application and continues throughout subsequent inspection and maintenance. Use of coatings in conjunction with cathodic protection (CP) is also an area which requires close attention.

Most coatings have an expected life span, though it may not be specified by the manufacturer. In order for a coating to live up to that life span, it is important that strict quality control be maintained prior to and during application of the coating. Failure to meet quality control at either of these stages will compromise the life span of the coating.

Regulations and guide specifications relevant for coating hydraulic steel structures (HSS) can be found in Part 2 of this two-part technical note series.

TYPES OF COATING SYSTEMS:

Lead-based: Lead-based paint gets its name from the lead pigment used in this type of paint. In the 1930s, nearly everything was painted with red lead and oil primer, with a phenolic aluminum topcoat. These coatings were maintained largely by touchup every 5–10 years and were completely replaced after 50–60 years. In 1978, a new law discouraged use of lead-based paint (CPSC 1977); however, new coatings systems to replace lead-based ones were already in place, so nothing new needed to be developed.

Urethane: A coating system that replaced lead-based paint consisted of epoxy zinc primer, epoxy intermediate coat, and a urethane topcoat. The moisture-cured urethane contains a zinc primer and uses two coats of an aluminum topcoat. Urethane paints contain a percentage of polyurethane chains that are highly durable and minimally affected by ultraviolet (UV) rays. Thus, urethanes are versatile because they can be applied over epoxies to provide UV protection. They can also be formulated as zinc-rich primers that are applied directly to steel. This category includes any and all polyurethanes.

Coal Tar: A common coating system is coal tar epoxy. It is made with coal tar pitch and epoxy resin, and therefore it is slightly difficult and hazardous to work with since it contains polynuclear aromatics and small quantities of carcinogens (<1%). Coal tar enamel has high viscosity and is therefore applied hot. Coal tar coatings are heavy duty and create high-build protective coatings. Today, coal tar enamel is only applied in a factory, such as on small-diameter pipe that will be buried. The blend of epoxy resin and coal tar provides an excellent protective barrier coating for steel, iron, and concrete. These systems have the potential to provide a significantly long service life. Pictorial examples of coal tar coatings are provided in Figure 1.

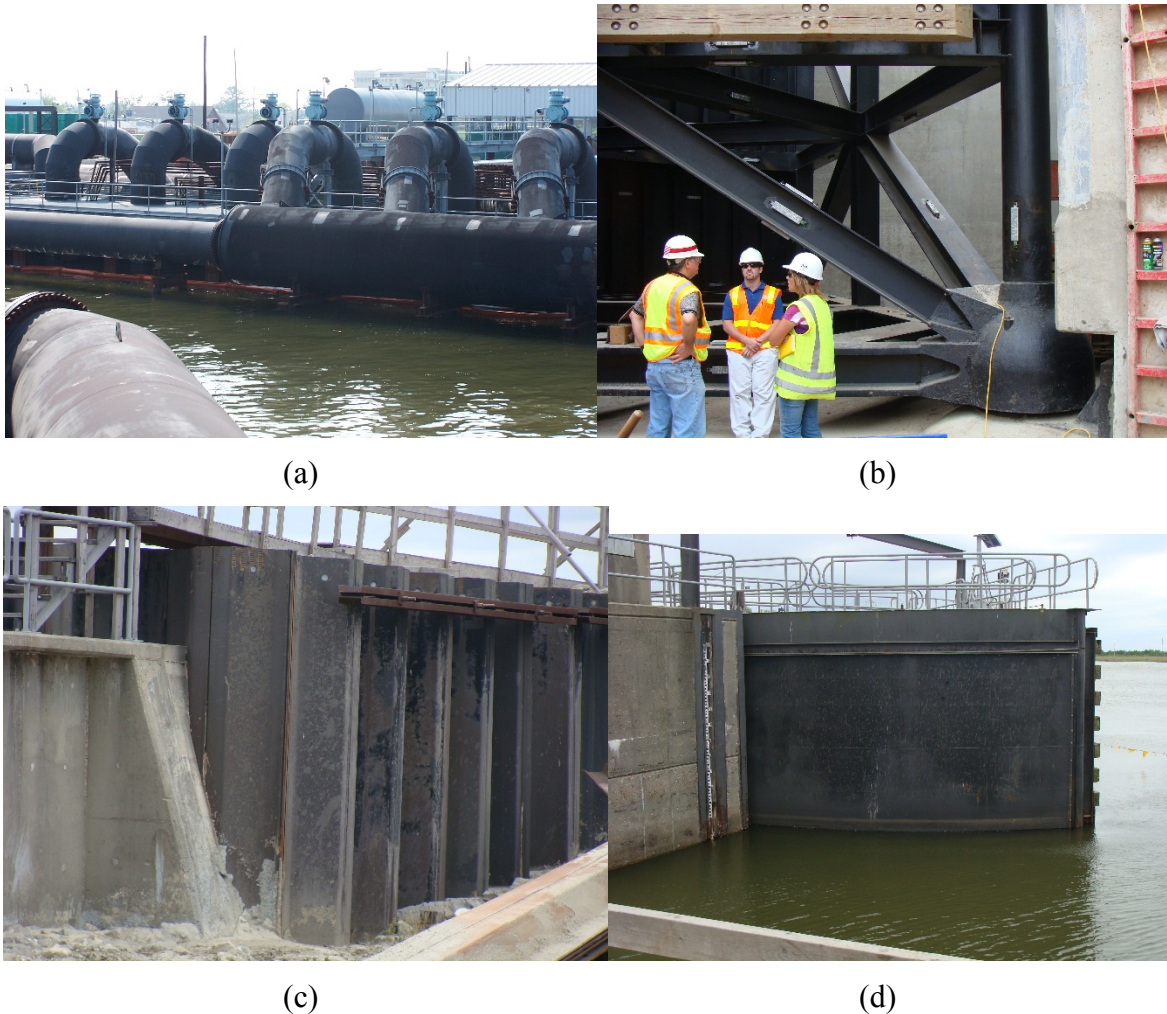


Figure 1. Examples of coal tar coating: (a) pumping station; (b) sector gate; (c) sheet piles; and (d) sector gate in brackish water.

Epoxy: Epoxy coatings consist of two parts: an epoxy resin and a co-reactant or hardener. When mixed, the epoxy resin cross-links with the hardener and creates a catalyzed coating which is hard, chemical-resistant, and solvent-resistant. Epoxy coatings are formulated based on the performance requirements for the end product. One particular formulation, Mil-DTL-24441, is an epoxy that is available in many colors, needs a urethane topcoat to protect from sunlight, and is used for above-ground fuel storage tanks. The downside to epoxy is the shattering that occurs when it is impacted by debris in turbulent waters.

Vinyl: Vinyl paints were developed by the Corps at its paint lab at Rock Island in 1947. The Rock Island lab was moved in 1973 to the U.S. Army Construction Engineering Research Laboratory (CERL) in Champaign, Illinois. Vinyls replaced phenolic coatings used previously. However, some of the phenolics applied in the 1940s are still in service. Some of the vinyls applied in the 1950s are also still in service. Vinyl can withstand abrasion because it is tough, and it displays high hardness and good chip resistance. Vinyl coatings are made of flexible plastic that adheres well to steel surfaces. It is designed to be sprayed and is not designed to be applied by other means. Vinyl

coatings have resulted in both very long and very short service lives. Photo examples of vinyl coatings are provided in Figure 2.



(a)



(b)



(c)

Figure 2. Examples of vinyl coating. (a) Tainter and roller gates on the Mississippi; (b) 50-year-old vinyl on miter gate; and (c) closure gate in New Orleans.

In 1969, a vinyl zinc primer was developed by the Corps. Many of the original vinyl applications are still in use today, and their condition depends on the water conditions and the environment they have been subjected to. Vinyl paints result in one coat of a given thickness because each spray pass melts into the previous pass. The final thickness is all that counts for quality, not the number of passes. The benefit of a zinc-rich primer is that rust will not creep under the edge where a spot was missed or under cracks. Vinyl can withstand the extreme impact of debris in turbulent water better than any other coating. An alternative to vinyl is epoxy, which is hard and water resistant, but it is also brittle and prone to chipped edges.

Inorganic: Inorganic coatings include those which do not fit in any of the above categories. These coatings include polysiloxane coatings and foul-release coatings. Zinc-rich primer, a common coating used within the USACE, is a polysiloxane-based coating. These inorganic coatings do not contain carbon chains, but do contain chains of other elements. Silicone is a common backbone element.

Thermal Spray: Thermal spray coatings are an alternative to paints and are typically chosen for applications that must withstand high wear. Thermal spray coatings have a much higher degree of hardness compared to paints because they are typically metal, but they could also be made with a metallic compound. Their surface bonding may be accomplished by mechanical, chemical, or metallurgical means, or by a combination of these. During application, a feedstock material is heated and propelled as individual particles or droplets onto a surface, where it flattens and forms a platelet-like structure as it cools. The thickness of the coating is determined by the amount of material deposited. Metallic thermal spray coatings may be either anodic or cathodic to the underlying metal substrate, but anticorrosive coating systems are generally designed such that the coating material is anodic to the substrate metal. This type of metallic thermal coating is also called metalizing.

WHERE ARE COATINGS APPLIED?: Coatings can be applied to any structure, whether it is above or below ground. Structures above ground are referred to as superstructures. Examples of superstructures include water storage tanks, power plants, buildings, and roofs. Examples of structures that are immersed in water or buried in the ground include miter gates, tainter gates, sector gates, sheet piles, underground fuel storage tanks, and buried pipes.

Water alone does not typically damage most coatings. However, debris in the water can cause abrasion and can cause impact damage to the coating. As stated previously, vinyl can withstand abrasion because of its toughness and chip resistance. Vinyl coatings perform well for flow, impact, and abrasion resistance; therefore, vinyl is suitable for use on immersed structures. Epoxies are used in a number of applications, including potable water tanks, because they are approved for such use.

General recommendations for use of the various coating types are: moisture-cured urethane systems are recommended for superstructures only. Vinyl paint is recommended for structures below water. Vinyl paints can only be used in fresh water, and they are typically used on miter gates and tainter gates. Vinyl paint doesn't work in brackish water; therefore, epoxy must be used in that type of water condition.

The problem with epoxy coatings is a tendency for the edges to chip easily. Epoxy based coatings have been in use for some time; however, in 2009 moisture-cured urethanes were introduced to

address the brittle nature of the epoxy and resultant chipping near the edges. Thus, in 2009, a new Unified Federal Guide Specification (UFGS-09 97 02) recommended a moisture-cured urethane primer and topcoat, which proved easier to apply. However, epoxy-based paints are still used on fuel storage tanks, because those tanks are governed by UFGS-33 56 10, “Factory-Fabricated Fuel Storage Tanks.”

Coal tar enamel coatings are best used for underground applications because exposure to sunlight will cause degradation. It is applied hot but is not used much anymore, especially in the field. Coal tar epoxy is used on buried pipe, sheet pile, and concrete. Coal tar has been used on sheet piles and sector gates in New Orleans.

Oil-based paints were previously applied directly to mill scale but now, surface preparation almost always includes white metal blasting because of the rationale that higher-performance coatings are commonly applied after higher grades of surface preparation.

The USBR and USACE have a variety of differences in their service environments. USBR typically has high head dams, where the sediment and debris settles out prior to getting to the dam structure. As a result, various other coating systems including epoxies and polyurethanes provide satisfactory coating performance in these applications. The Corps normally has structures in navigation and flood control environments, where debris and sediment typically do not settle out prior to reaching the structure. Therefore, the Corps’ coatings are subjected to higher erosion and impact than occurs on Reclamation’s infrastructure. Impact and/or sediment cause a faster degradation rate than the rate that occurs in static submerged conditions. Epoxy coatings also have worse impact and erosion resistance, when compared to vinyl resins, because they are brittle. This is why the Corps does not use epoxy coatings.

The USBR has a few sites with successful use of metalized coatings that have lasted 20-30 years. However, one site with metalized stop logs has signs of corrosion after only 2 years. This may have been due to improper application. The use of metalized coatings by the USBR is rare and the criteria for use include atmospheric exposure (not submerged). The Blue Mesa Dam is one site that has metalized gates which are still in good shape since installation in the 1980s. The rationale for use of metalized coatings was that epoxy was too brittle and vinyl was not being used by the USBR at that time. Reclamation has recently begun laboratory testing of vinyl paints after a 20-year hiatus.

USACE is also using metallizing in intense abrasion areas on some tainter gates because it can withstand the intense abuse much better than nonmetallic coatings. However, in quieter water, nonmetallic coatings will provide a much longer service life.

INTERVIEW WITH A COATINGS EXPERT – CERL PAINT TECHNOLOGY CENTER:

Information in this section was obtained during an interview with personnel from the Engineer Research Development Center – Construction Engineering Research Laboratory (ERDC-CERL) Paint Technology Center (Beitelman 2015). The center employs several coatings experts, some of whom have worked for the Corps since the early 1970s.

The Paint Technology Center has a long history of coating inspection. Paint Center personnel have inspected all types of coatings in all types of environments and have witnessed many types of

failed coatings. Center personnel have seen coatings that have lasted longer than their expected lifetime and have also seen those that failed very quickly.

Visual inspection is the primary method for inspecting coatings. Paint Center personnel have travelled to many areas of the country to visually inspect coatings. All photos in this Technical Note were taken by Mr. Beitelman and collectively, they represent the types of coatings he has inspected, including examples of the failure mechanisms mentioned above.

An example of poor quality control and poor inspection is a coating that was applied over masking tape. Needless to say, this coating did not last long at all. Factors playing into this coating failure included the application over masking tape as well as the coating was too thin. Both of these problems could have been prevented with better quality control, obtained through inspection before and during the coating process.

An example of a long-lasting coating is the one which was applied to hydro plants near Portland, Oregon. A 2013 report documents the current condition of coatings applied in the 1940s through the 1960s (Paint Technology Center 2013). Many of these coatings were oil-based systems with lead-pigmented primers, some of which were still providing excellent corrosion protection.

Maintenance of coatings within the Corps is varied. Some districts conduct periodic maintenance or touchup; however, a lot of districts do not. Maintenance costs are high because of the cost to mobilize work crews. Many times, gates are not maintained until the entire structure is repainted. The proximity of the structure to the public (metropolitan areas) also drives maintenance intervals. The desire to present a good appearance near metropolitan areas often times leads to more frequent re-coatings.

From the perspective of the Paint Technology Center, paint is cheap compared to coating maintenance costs. Of all the costs related to coatings, mobilization and surface preparation are the highest. To be considered a good coating, a coating must have not only quality paint but also have quality control. In other words, for a paint to live up to its quality, it must be applied correctly.

Many coatings are two- or three-component systems that need to be properly mixed. Precise mixing is achievable in the lab, but field mixing is often less precise and requires close quality control. Applying a coating uniformly in the field can also be a challenge. A field-applied coating may ultimately fail for any or all these reasons—poor field mixing and quality control, and/or lack of coating uniformity.

Another cause of coating failure is the improper use of CP. High CP voltages can destroy coatings. An example in Mobile District was discovered when some gates that were in the water for 38 years were removed; the gates had no rust, but the paint was bubbled around anodes and corners where there was elevated potential. It is common for overvoltage to destroy coatings. This is not a problem for sacrificial anodes, only for impressed current systems which can be turned up above the 1.4 volt threshold. This overvoltage condition may exist when the CP voltage is not continuously monitored. An example of coating failure from CP overvoltage is shown in Figure 3



Figure 3. Example of failure from CP overvoltage.
Sacrificial anode caused blistering of coating.

Many other types of coatings failure and examples of each can be found in Part 2 of this Technical Note series.

INTERVIEW WITH A COATINGS EXPERT – U.S. BUREAU OF RECLAMATION: Information in the following section was obtained from survey data supplied by the USBR (Skaja 2015). The coatings expert who was interviewed has been with Reclamation for 10 years.

Historically, the USBR used vinyl resins, coal tar enamel, and lead-based paints throughout their projects. In the 1970s, Congress passed the Clean Air Act and the Clean Water Act, and these laws severely reduced the use of coal tar enamel and lead-based paints (CPSC 1977). In 1992, the EPA placed restrictions on how manufacturers of high volatile organic compound (VOC) coatings could market their products (EPA 1997). Other regulations developed by state EPAs reduced the allowable VOCs used in industrial maintenance coatings. In turn, the EPA was persuaded to form a category called “impacted immersion” specifically to allow use of vinyl resins for harsh service conditions. Today, the only users of vinyls in the United States are the Corps, the Tennessee Valley Authority (TVA), and the St. Lawrence Seaway system, because most manufacturers have decided to no longer make the vinyls (e.g., PPG/Ameron, International Paint). In 2009, Dow Chemical decided to stop manufacturing the vinyl resins (raw ingredients), leaving Wacker as the most reliable remaining supplier of vinyl resins.

In 1992, the Reclamation’s coating specialists decided to stop using vinyl resins and began using commercially available epoxy coatings to meet VOC regulations. The Reclamation’s vinyl formulations were lost until 2015, when collaboration with USACE turned up old USBR formulations found in the ERDC-CERL Paint Technology Center.

Commercial epoxy coatings have varying life expectancies of 15–20 years. Reclamation’s first-known application of epoxy was in 1985 on the spillway radial gates at Yellowtail Dam. The coating is still performing well. There is also a CP system installed on the gate, so CP may have helped contribute to the 30⁺ years of service. Without CP, the coating may have only lasted the expected 15–20 years. CP is clearly extending the service life of newer coating systems. Mr. Skaja believes

the USBR needs to use CP in conjunction with coatings on infrastructure in order to obtain a service life that is desired.

Mr. Skaja started with Reclamation in 2005, and he has rebuilt the coatings testing lab. The lab now has specialized equipment (electrochemical impedance spectroscopy) to evaluate coatings for corrosion protection. They have observed that the old coal tar enamel and vinyl resins provide a completely capacitive coating for the life of the materials. Epoxy coatings impedance values typically decrease with time, as water and ions migrate through the coatings. Recent findings show that aromatic polyurethanes that meet the AWWA C222 standard (AWWA 2008) and silicone foul release coatings show similar capacitive behavior. Denver Water has a polyurethane that is 20 years old in a 10-ft diameter pipe that has no corrosion and no CP system. The polyurethanes show great promise for the future; they hope to see a 40⁺-year service life with the polyurethanes. The foul release coatings are used to control invasive mussel fouling. These coatings have not been on the market a very long time, but are becoming more popular in the shipping industry because they provide increased fuel efficiency due to the silicone coating's hydrophobic nature. Both polyurethane and foul release coating systems provide an increased erosion resistance compared to epoxy coatings. The foul-release coatings have poor abrasion, impact, and gouge resistance and would not be recommended in service environments that experience such conditions.

Another newer technology that the USBR is investigating is the polysiloxane coatings (e.g., PPG PSX 700 and Sherwin Williams [SW] Polysiloxane XLE80). They recently found out that PPG and SW have started recommending these coatings for water immersion service. The first-known application to a radial gate was at TVA's Fontana Spillway Gate. There they applied two coats of epoxy followed by one coat of PSX 700. NACE Paper No. 477 (Brevoort and McLampy 1996), contains data that shows the service life expectation is greater for atmospheric exposure than it is for a zinc-rich epoxy, epoxy intermediate coat, and polyurethane topcoat.

Guide specifications are available on the USBR website and, they are different than either the Department of Defense (DoD) or USACE guide specifications. Reclamation typically lists product names and manufacturers and selects products for a particular service environment, whereas DoD and USACE write performance and product specifications, called military specifications.

The USBR does not have much long-term experience with epoxy coatings. In general use, the epoxy coatings sometimes last 10–15 years, while others last 30 years. Reclamation has only been using the aromatic polyurethanes for 10 years, but has had only one premature failure (due to insufficient surface preparation).

Reclamation has also developed an erosion test, a fluctuating water test, and a high flow water immersion test. It is in the process of building a cavitation tester in accordance with ASTM G132 (ASTM 2013). From the USBR's erosion test results, the polyurethanes have about 10 times better erosion resistance compared to vinyl resin, and polyurethanes have about 30 times better erosion resistance than epoxy coatings.

The USBR has identified premature coatings failures in several applications and has made other observations, which are described below:

- A penstock polyurethane coating delaminated in a 40 foot long sheet 4 years after service. A crack formed in the coating at a sleeve coupling joint. Water got behind the coating and stripped out the coating.
- On a gate, a contractor didn't follow the specifications in the area of the rivets, leading to premature failure of the coating.
- On another gate, where polyurea was applied, the contractor missed the recoat window and unfortunately, the contractor was not forced to re-abrasive blast and start over, causing failure in just a few years.
- On stay vanes, coal tar epoxy delaminated. The cause is unknown, but believed to be improper surface prep or adverse environmental application conditions. However, several cases of coal tar coatings lasting beyond their expected lifetime have also been recognized.
- In general, coal tar enamel, vinyl resins, and lead-based paints are amazing. They have extremely long service lives; however, their use has significantly decreased due to new regulations, including VOC limits.

Reclamation conducted a 20-year inspection of the Denver Waters' polyurethane coating. The success lead the USBR to specify and recommend more polyurethane coatings. However, the unexpected delamination of a polyurethane in their Flatiron penstock in 2015 caused the USBR some concern. A recent laboratory test showed that manufacturers have developed polyurethanes that have better adhesion to steel and should not delaminate in the same fashion. The lesson learned was that under shear conditions, it is important to specify the correct polyurethane coatings to eliminate the potential premature failure. In static or low-velocity flow, any of the polyurethane coatings would be a good choice.

To achieve a maximum service life for the USBR projects, a 5–10 year maintenance cycle should be planned to repair corrosion, but this is rarely done due to inaccessibility of the structure. The old historic coatings provided a 40–50 year service without the need to conduct spot repairs. Coatings specialists have been preaching for a while about the importance of maintenance planning but overall, the USBR is just now starting to understand the importance of maintenance planning.

In the past, visual inspection was the method of monitoring corrosion and condition of coatings. However, this technique is a qualitative evaluation and is not very accurate. Reclamation has begun using field electrochemical impedance spectroscopy (EIS) to monitor coating conditions. Even if the corrosion is not visible to the naked eye, EIS will detect the corrosion under the film when there is as little as 0.0001% corrosion. The EIS method is extremely accurate for whatever area is being evaluated.

The USBR conducts a variety of accelerated weathering tests and although Mr. Skaja did his doctoral thesis on accelerated weathering, the most important thing he learned during that time was that there is not a single test that will simulate exact field conditions.

SUMMARY: This technical note has summarized the different types of coating systems available for use on hydraulic steel structures, their pros and cons, and many of their typical applications. Many of these coatings work reasonably well and serve the purpose of protecting the structure from corrosion. Coating experts have pointed out a number of common problems that can plague the success of a coating, creating premature failure, and leading to signs of corrosion on the structure. With this knowledge in mind, the needs and constraints of design engineers can be better

addressed, to improve the effectiveness of corrosion prevention and control practices across the Corps. This knowledge will also serve other agencies, organizations, installations, and communities throughout the country.

FUTURE WORK: Results of the field survey and the information gathered have helped gain a greater perspective on the use and condition of coatings around the Corps, as well as the USBR. Further investigation into the wide variance in inspection and monitoring of coatings could be highly useful for USACE Headquarters as well as Districts, to better plan for increasingly scarce maintenance dollars.

This work will culminate in guidance to the Corps for improved quality control, measurement, inspection, and maintenance of coatings. Future work could include updates to relevant guidance documents and/or new specifications. More widespread use of a simple rating system and collecting that information in a database could be an efficient and useful tool for managers and policy makers.

Future site visits will include specific inspections of coating systems and their conditions. This technical note has helped shape the kinds of questions to ask and the types of coating failures to look for.

POINTS OF CONTACT: This CHETN is a product of the Water Resources Infrastructure Work Package of the Civil Works Business Area, being conducted at the U.S. Army Engineer Research and Development Center, Construction Engineering Research Laboratory.

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